Ninth International Conference on
THIN-WALLED STRUCTURES – ICTWS2023
Sydney, Australia, Nov 29 – Dec 1, 2023

RETROFIT METHOD FOR REPAIR OF CORRODED BOLTED CONNECTION

Eiki Yamaguchi, Naomichi Tamada, Urantogos Agvaanluvsan and Toshikazu Takai

Department of Civil Engineering, Kyushu Institute of Technology, Japan
e-mail: yamaguch@civil.kyutech.ac.jp

Keywords: Bolted Connection; Corrosion; Retrofit; Connector Element.

Abstract. *For the repair work of a corroded bolted connection, common practice is to use a temporary bent. In case the bent cannot be set up, an extra member called a bypass member is installed over the connection. The repair cost of either method would be quite high. The present study explores the retrofit method that requires neither a bent nor a bypass member. In the proposed method, bolts would be replaced row by row, the unevenness of the splice plate surface is fixed and the splice plate is reinforced little by little by a slice of plate. The validity of the method is investigated by analyzing the bolted connection with the bolt layout of 23 rows by 4 columns. To this end, the usage of a connector element for modelling a bolt is studied beforehand. The comparison with the results by the 3-D solid element analysis and the experiment confirms the validity of the employment of the connector element for bolt simulation.*

1 INTRODUCTION

One of the most critical phenomena that could control the service life of a steel bridge is corrosion. Because of the complexity of its geometry, the quality of painting tends to be lower in a bolted connection than that in any other part of a steel bridge and water tends to be stuck in a bolted connection. As a result, a bolted connection is often found severely corroded. An example is given in Figure 1. It was located on the top flange of the beam in a steel moment frame supporting expressway. There seemed water leakage at the end of the girder that led to the corrosion.

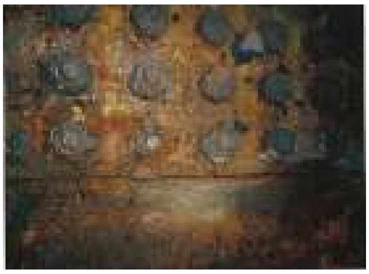
For the safety of a bridge, a corroded bolted connection has to be repaired. Bolts are to be replaced and a splice plate is to be replaced or reinforced. To conduct such a construction work safely, common practice is to use temporary bents. In case the bents cannot be set up, an extra member is installed over the connection, which is called the bypass construction method. Either work is often accompanied by the regulation of traffic. Not only construction cost but also social cost would occur in that case.

The present study explores the retrofit method that requires neither a bent nor a bypass member. It wouldn't impose traffic regulation. In short, in the method, bolts would be replaced row by row and the splice plate would be reinforced little by little: a slice of plate would be put on the damaged splice plate after fixing the unevenness of the splice plate surface due to corrosion. This retrofit procedure is as it were an incremental method. It reduces safety margin, but the reduction would be small and only for a short period of time. Therefore, it is expected the required safety is satisfied without a bent or a bypass member,

2 NUMERICAL APPROACH

The finite element method is the mainstay of the present study. At the current state, it is possible to model a bolt by solid elements as they are. However, the computational cost

(a) Overview



(b) Bolted connection

Figure 1: Corroded bolted connection.

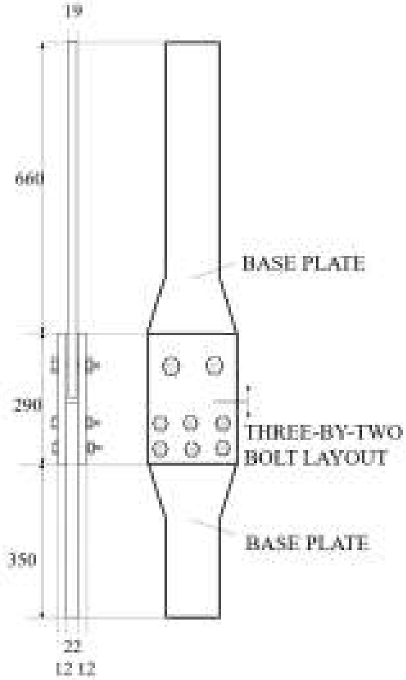
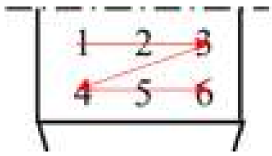
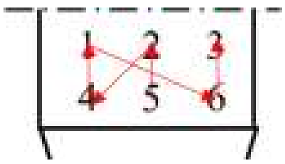


Figure 2: Bolted connection with the bolt layout of 3 rows by 2columns.



(a) Overview



(a) Overview

Figure 3: Corroded bolted connection.

including the modelling would become very high. It cannot be a choice from a practical point of view.

The software called ABAQUS [1] is to be used in this study. It has a connector element which connects two nodes and controls their relative motion. The present study tries to apply this element to simulate the mechanical behavior of a bolt. The connector element is so simple that computational cost would be much smaller than that of the solid element analysis. Therefore, the present study first explores a possibility for using a connector element to model the mechanical behavior of a bolt.

A connection with the bolt layout of three rows by two columns is studied. To be specific, the bolted connection in Figure 2 is considered. As a repair work, bolts are replaced herein. The connection is analyzed by two models, the sophisticated model using 3-D solid elements and the connector-element model. The replacement of a bolt is carried out by the removal of a bolt followed by the installation of a new bolt, and this process is simulated in the analyses.

Tensile load is applied to the connection. The magnitude is just about 1/1.7 of the slip load. Two bolt-replacement patterns are considered, as shown in Figure 3. Pattern 123456 is the bolt replacement in the order of 1, 2, 3, 4, 5 and 6, while Pattern 524163 in the order of 5, 2, 4, 1, 6 and 3. Accordingly, two different analyses are conducted by each finite element model. The

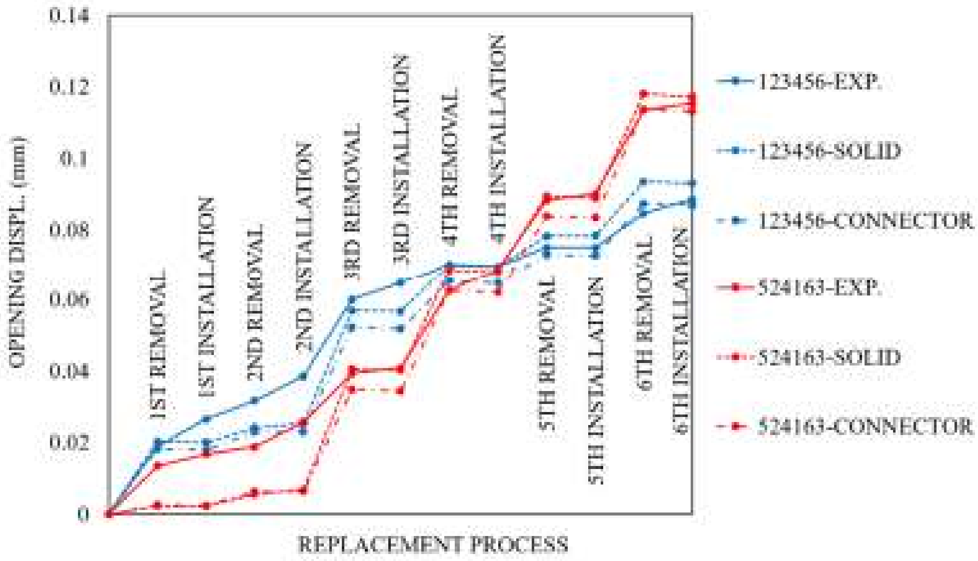


Figure 4: Opening displacement

Figure 5: Experiment.

opening displacement, the gap between the base plates, is computed in each analysis. It could change with the removal of bolts.

The numerical results are presented in Figure 4. The blue dotted line is the opening displacement by the 3-D solid elements for Pattern 123456. It can be seen that the opening displacement increases with the bolt replacement. The blue dashed line is the opening displacement by the connector element analysis for Pattern 123456. It captures the same tendency in the opening-displacement variation. The two lines indicates that the difference between the results of the two analyses appears quite small.

The red dotted line is the opening displacement by the 3-D solid elements for Pattern 524163. The opening displacement increases with the bolt replacement also in this replacement pattern. To be interesting, the way the opening displacement varies is different from that of Pattern 123456: initially the opening displacement is smaller than that of Pattern 123456, but it becomes larger at the end. The importance of the repair order is recognized.

The red dashed line is the opening displacement by the connector element analysis for Pattern 524163. It captures the same tendency in the opening-displacement variation, and in fact the difference between the results of the two analyses is again insignificant.

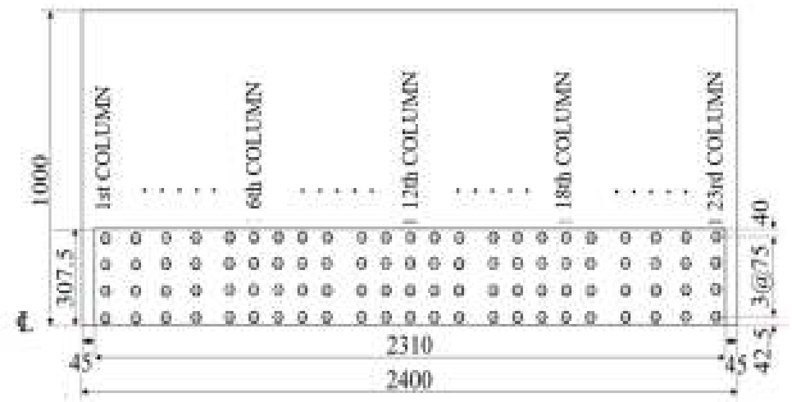


Figure 6: Plane view.

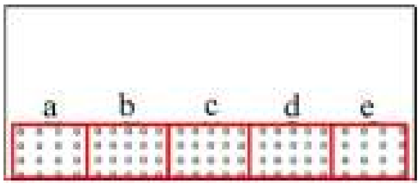


Figure 7: Bottom splice plate.

From the two analyses, it can be stated that the connector element can be used to model the mechanical behavior of a bolt.

To see the validity of the present numerical approach, experiment is conducted (Figure 5). For each bolt-replacement pattern, three specimens are tested. The average of the experimental results is shown in Figure 4 by solid lines. In the beginning when the opening displacement is small, the experimental results are larger than the numerical results in both of the bolt-replacement patterns, yet the difference decreases as the bolt-replacement progresses and the opening displacement increases. The same tendency as that of the numerical results is observed in the experiment: Initially the opening displacement of Pattern 123456 is larger, but that of Pattern 524163 becomes larger at the end.

The experimental result thus validates the numerical approach employed in the present study.

3 RETROFIT METHOD

Based on the existing corroded bolted connection, a bolted connection is constructed and the retrofit method is studied. The bolted-connection model herein is shown in Figure 6. Each splice plate has the bolt layout of 23 columns by 4 rows. The thickness of the base plate is 19 mm, the thickness of the top splice plate 11 mm and the thickness of the bottom splice plate 12 mm. The top splice plate and the bolts are supposedly corroded badly.

To take account of the deterioration due to corrosion, the thickness of the top splice plate is reduced by 3 mm and the axial force in the bolt is by 25%. The retrofit work is to replace bolts, fix the unevenness of the splice plate and put a slice of plate for reinforcement. The bolt replacement is conducted columns by column. When bolts are removed, the unevenness is fixed, a slice of plate is placed and new bolts are installed. The thickness of the additional plate is 12 mm. As shown in Figure 7, the bottom splice plate consists of 5 plates, Plates a to e, because of the longitudinal stiffeners. The retrofit work is therefore carried out for each area of those 5 splice plates.

The safety is lowered by the removal of bolts. The splice plate may slide on the base plate and the opening displacement increases. The load that causes the opening displacement of 0.2

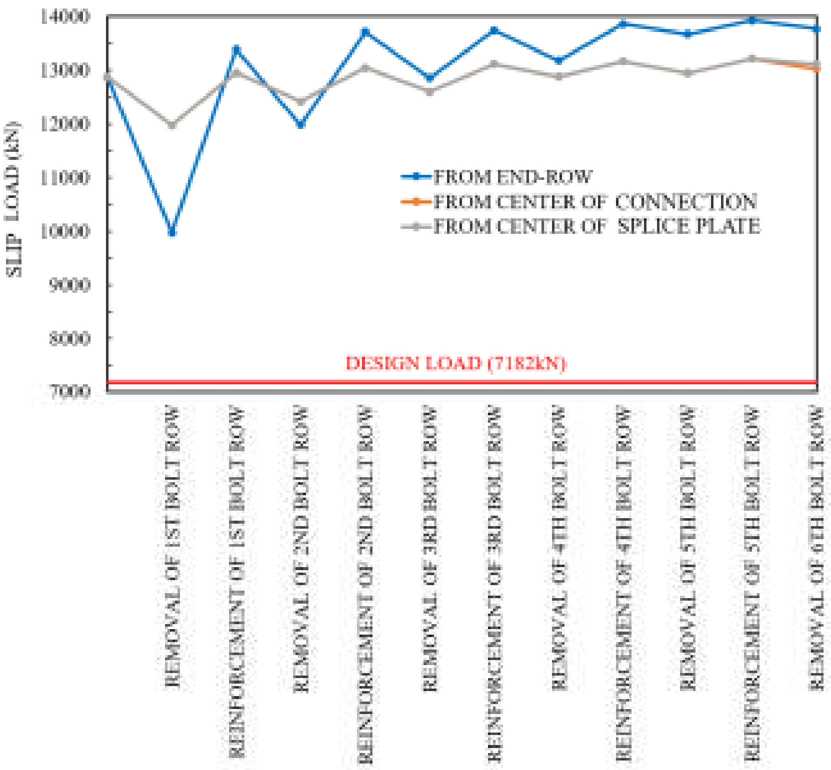


Figure 8: Slip loads.

mm is the slip load. If the removal of bolts leads to the slip load smaller than the design load, that bolt removal cannot be admitted.

In the present study, the slip load is computed by the finite element analysis. Shell elements are employed for a base plate and splice plates while connector elements are used for bolts. The coefficient of friction between the base plate and the additional plate is assumed 0.5, following the work by Tamba et al. [3].

Three retrofit patterns, Patterns (a) to (c), are studied first. In these patterns, the repair is conducted one row by one row. In Pattern (a), the repair is done in the order of Plates a, b, c, d and e. In each plate, the repair is carried out from the row near the end of the connection. In Patterns (b) and (c), the repair is in the order of Plates c, b, d, a and e. In Pattern (b), the repair starts from the row near the center of the connection, while in Pattern (c), the repair from the row near the center of the plate.

Figure 8 shows the slip loads. The retrofit processes of Patterns (b) and (c) are exactly the same up to the reinforcement of the 5th bolt row. The slip load is small when the bolts in the 1st bolt row are removed in each pattern. The smallest slip load is observed in Pattern (a). The difference between Pattern (b) and (c) appears at the removal of the bolts in the 6th bolt row, and the slip load of Pattern (b) is smaller. The best repair procedure of the three is therefore Pattern (c). The result here indicates that it is better the repair is carried out near the center of a connection and near the center of a splice.

For the sake of safety in a repair work, it is desirable to repair a bolted connection one row by one row. However, it would be more efficient if multiple rows are fixed at one time. Therefore, another four retrofit patterns, Pattern (d) to (g) shown in Table 1, are tried. In the table, for example, "3 rows + 2 rows" means that three rows of bolts are removed at one time and repaired, which is followed by the retrofit of two rows. In all the patterns, the repair is carried out from the plate near the center of the connection, i.e. in the order of c, b, d, a and e.

The finite element analysis of the four retrofit patterns reveals that upon the removal of all the bolts in five rows of Plate c, the slip load reduces to 5340 kN while the design load is 7182

Table 1: Retrofit patterns.

	Plate c	Plates b, d	Plates a, e
(d)	3 rows + 2 rows	3 rows + 2 rows	2 rows + 2 rows
(e)	5 rows	5 rows	4 rows
(f)	5 rows	5 rows	2 rows + 2 rows
(g)	5 rows	3 rows + 2 rows	2 rows + 2 rows

kN. Hence, Patterns (e) to (g) are not acceptable. In Pattern (d), even the smallest slip load exceeds 9000 kN, which is well above the design load.

4 CONCLUDING REMARKS

The retrofit method for a corroded bolted connection was explored. To this end, the possibility of modelling the mechanical behavior of a bolt by the connector element was investigated carefully first. The validity of the connector element has been confirmed by the sophisticated analysis with 3-D solid elements and the experiment.

A practical bolted connection with the bolt layout of 23 rows by 4 columns was analyzed using connector elements. The numerical study shows that the proposed retrofit method can be applied safely, keeping the slip load above the design load. The bolted connection would be safe during the repair work without installing a bent or attaching a bypass member. It was also found that for the sake of efficiency, the retrofit could be performed up to three rows of bolts at one time.

REFERENCES

[1] Dassault Systemes Simulia Corp., *User's Manual, ABAQUS Ver. 6.13*, 2013.

[2] Shimozato T., Tai M., Arizumi Y., Yabuki T., Nagamine Y., "A study on evaluation for residual axial force of corroded high strength bolts", *Journal of Structural Engineering*, JSCE, 59(A), 725-735, 2013.

[3] Tamba Y., Yukito S., Yamaguchi T., Sugiura K.,Higatani A., Tabata A., "Experimental study on static behavior of the high strength bolted joints which have some concavities and filled up with and applied adhesives in the surface", *Journal of Structural Engineering*, JSCE, 60(A), 703-714, 2014.